

Events registration in a fast neutrons spectrometer

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Abstract

The principle of operation, design, registration system and main characteristics of a fast neutrons spectrometer are described. The spectrometer is intended for direct measurements of ultra low fluxes of fast neutrons [1]. It is sensitive to neutron fluxes of $10^{-7} \text{ cm}^{-2}\text{s}^{-1}$ and lower. The detection efficiency of fast neutrons with simultaneous energy measurement is within 0.03–0.09 for neutron energies $>0.7 \text{ MeV}$ and depends on the neutron energy and the spectrometer response function.

The neutron spectrometer was designed taking into account requirements for minimizing the γ -ray and random coincidence backgrounds. It is a calorimeter based on a liquid organic scintillator-thermalizer with helium proportional counters of thermalized neutrons distributed uniformly over the volume. The energy of thermalized neutrons is transformed into light signals in a scintillation detector. The signals from proportional counters provide a “neutron label” of an event.

Low-level signal electronics for the spectrometer were designed with signal-to-noise ratio optimization and full pulse shape analysis required for efficient rejection of background events. A data acquisition and processing system is based on fast (100 MHz) two-channel PC/AT interfaced digital oscilloscope. The acquisition software was written in the C programming language.

1 Principle of operation and design of the spectrometer

The detection part of the spectrometer (detector) consists of an organic scintillator viewed by photomultipliers (PMT) and proportional counters with ^3He (neutron counters — NC) distributed uniformly over the scintillator volume. Figure 1 shows a general view of the detector. Fast neutrons ($E_n > 1 \text{ MeV}$) enter the scintillator, are decelerated down to thermal energy, and diffuse in the detector volume until they are either captured in a neutron counter or captured by scintillator protons or leave the detector. The amplitude of light scintillations from recoil protons, which are produced during neutron thermalization, is on average proportional to the initial neutron energy, if the energy losses due to scattering by carbon and a non-linear dependence of the scintillator light yield on the energy of recoil protons are

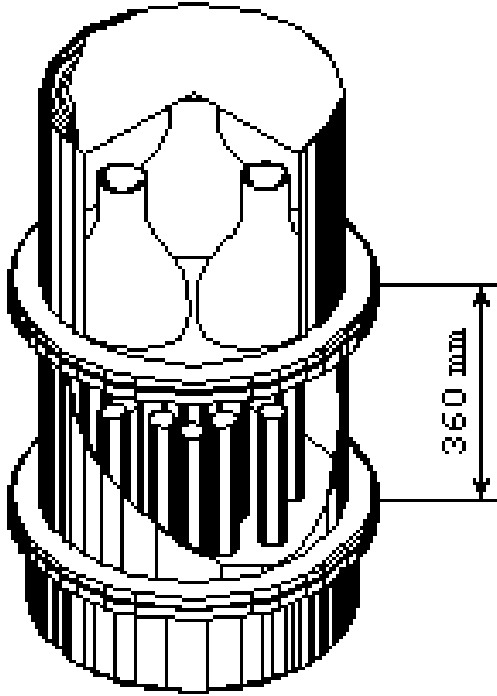


Figure 1: General view of the detector

neglected. A portion of thermalized neutrons in the neutron counters is captured by ^3He nuclei, which emit protons and tritium nuclei.

To simplify the apparatus structure, signals from all PMTs and counters are multiplexed into independent channels called “PMT channel” and “NC channel” respectively. A signal from NC channel triggers the data acquisition system. The full waveforms of events in the PMT and NC channels are registered independently inside selected time interval before and after trigger, which are called “prehistory” and “history” accordingly, by means of two-channel digital oscilloscope. This time interval can be adjusted in the acquisition algorithm over the wide range from $0.2 \mu\text{s}$ to 2.6 ms and is selected on the basis of calibration measurements.

There is a certain distribution of time intervals between appearances of a signal from PMTs and a signal from one of the NCs related with one neutron, which is associated with specific characteristic feature of the detector — delay. This delay is conditioned by the mean lifetime of thermalized neutrons inside the detector volume and is determined mainly by the detector design. If at least one event occurs in the PMT channel during the acquisition time interval, it is “labelled” as the signal coinciding with neutron capture in the NC. The amplitude of the labelled PMT signal is considered as a measure of the initial neutron energy. This technique for collecting events allows one to significantly (by several orders of magnitude) suppress the natural background of γ -rays.

The detector housing is made of stainless steel. The volume of cylinder tank for scintil-

Table 1: Basic performance data of the preamplifier and linear summators

Characteristics	Preamplifier	Summator NC (PMT)
Gain (K)	2.5–5, variable	inverting -1 (-1 – 5 , variable)
Max. out voltage, V	-2	$+2$ ($+3.5$)
Load impedance, Ω	50	50
Risetime, ns	16 (K=5), 6 (K=2.5)	9 (3)
Bandwidth	100 Hz – 20 MHz (K=5)	100 Hz – 40 (100) MHz
	100 Hz – 55 MHz (K=2.5)	
Output noise (PA on)		~ 3 (≤ 1) mV, $2U_{max}$
Dynamic range		≥ 500 (3500)
Power requirements	± 12 V, ± 16 mA	± 12 V, $+111/-105(+25.5/-22)$ mA

lator is about 30 l (taking into account the volume of NCs). To enhance light collection, the walls and bottom of the scintillator tank were coated with a fluoroplastic, and 19 wells for NCs were coated with aluminium foil. An illuminator made of organic glass was covered by fluoroplastic disk with windows intended for improving light collection and securing three PMTs Model 173. PMTs, preamplifiers, and a summator of PMTs signals were placed under the light-protecting cover.

CHM-18 neutron counters filled with a ($^3\text{He} + 4\%\text{Ar}$) mixture at a pressure of 4 atm are mounted in sealed wells in the interior volume of the tank filled with the scintillator. The anode contacts of the counters are terminated under the lower tank plane. The preamplifiers of signals from NCs, and the signal summator are placed in the bottom part of the detector and are also covered with a cap. The Protva NE-213 scintillator used in the detector has the following characteristics: 0.84 g/cm³ (density); 136 g/kg (hydrogen concentration); 3 ± 0.6 ns (scintillation duration); a light yield of at least 40% of anthracene; and 80°C (combustion temperature).

2 Low-level signal electronics

2.1 Formation of the Initial Signals

Signals from the PMTs and NCs are amplified by the preamplifiers (PA), are multiplexed in the linear summators, and are entered into the data acquisition system. The circuit design of the low-level signal electronics are selected taking into account an optimal signal-to-noise ratio. Their basic characteristics are listed in the Table 1.

The anode circuit's capacitance of the PMT Model 173 is ~ 20 pF, and the time of electron collection by the anode is ~ 90 ns. The PMT anode load is 1 M Ω . Since the PA bandwidth ensures a sufficient margin with respect to the initial signal spectrum, an exponential pulse with a duration ~ 80 μs and a trailing edge time constant of ~ 20 μs forms at its output.

Difficult problem is to provide the necessary signal-to-noise ratio in the NC channel. Joining signals from 19 counters into a common channel increases the noise at the linear

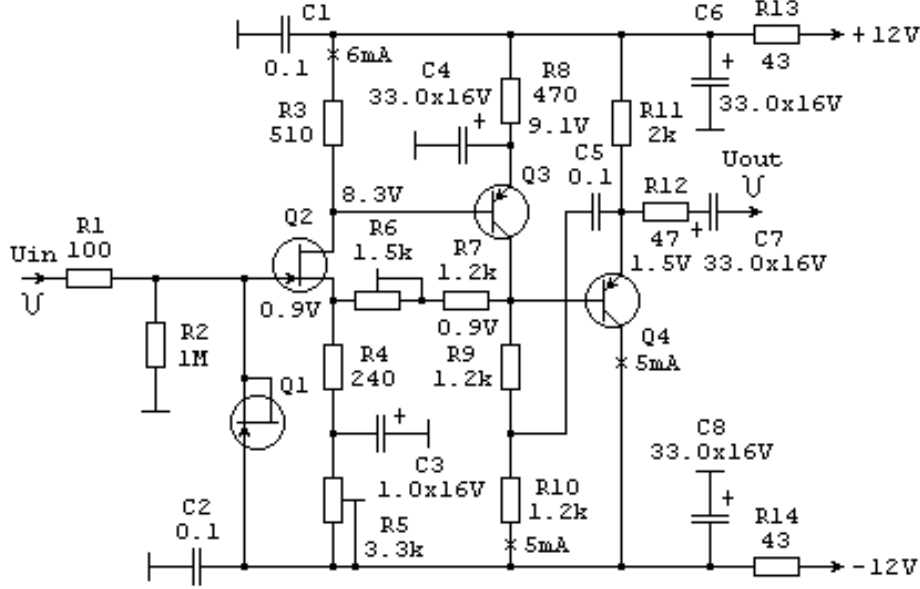


Figure 2: The circuit diagram of a fast low-noise preamplifier

summator output by a factor of at least 4.5. To reduce the noise, the main amplification of initial signals is accomplished with the preamplifiers before their joining. Figure 2 shows the circuit diagram of a fast low-noise preamplifier, which was developed especially for this purpose. It is used in both channels of the spectrometer: PMT and NC.

2.2 Preamplifier

The preamplifier has a two-stage common-source-common-emitter circuit with common serial negative-voltage feedback loop (NFL) and directly coupled stages. Each stage has a local serial, current NF. The first stage is based on a FET with normalized coefficient of the noise charge and has gain of 2, which also improves the noise characteristics of the PA as a whole. The third stage of PA is an emitter follower with bootstrapping over C_5 to common point of R_9 and R_{10} , which increase PA gain without common NFL 4–5 times. The total gain of PA with an open NFL is ~ 3750 . For a closed NFL, the gain is continuously adjusted from 5 to 10, and the minimum amount of feedback is ~ 50 dB. The parameters of PA circuit elements are selected so as to minimize the potential difference between the Q_2 source and Q_3 collector and thus to reduce the effect of parasitic capacitance of NFL elements on the PA speed. Its dc operating mode and gain are set with a trimmer resistors R_5 and R_6 , respectively. A protective circuit at the PA input is based on a FET Q_1 connected as a diode. The input impedance is determined by the R_2 value and equals $1\text{ M}\Omega$ in our case.

An output emitter follower isolates the NFL and load circuits and transmits pulses from PA to summator through an RG-174 coaxial cable with a $50\ \Omega$ characteristic impedance. Power matching conditions used in the device decrease the final gain by a factor of 2 without an appreciable decrease in the signal-to-noise ratio, but protect the PA output stage from shorting in the load, improve the linearity, provide the minimal distortions of the signal

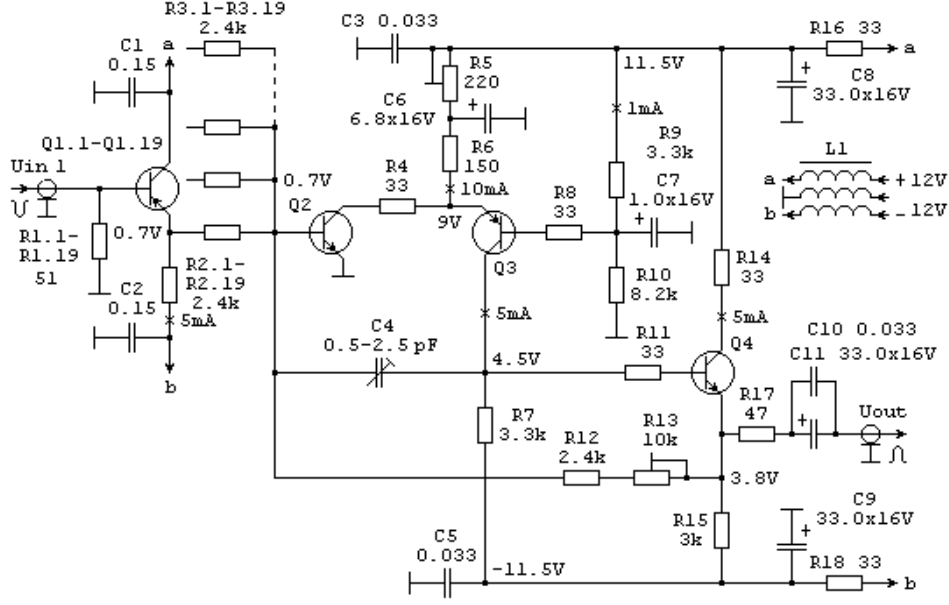


Figure 3: The circuit diagram of a fast low-noise linear summator (NC)

waveform, and simplify the spectrometer assembly, allowing for optimal wiring of circuits.

2.3 Linear Summators

2.3.1 NC channel

To attain the maximum signal-to-noise ratio, signals from NC preamplifiers were joined simultaneously in one stage for all 19 channels by using a fast low-noise linear summator which electric circuit diagram is shown in Figure 3.

The summator has a complementary cascode circuit with an output emitter follower on transistors Q_2 – Q_4 with a common parallel voltage NFL. The summator operation is based on the known principle of adding the input current signals, which are specified by the weight resistors $R_{3.1}$ – $R_{3.19}$, at a small input impedance of the amplifier with a parallel NFL applied.

The input impedance of the cascode circuit is $250\ \Omega$ for a collector current of 5 mA and a typical $h_{21e}=50$. The amplifier gain with an open NFL is ~ 660 . The gain with a closed NFL is set at 2 for each input by using trimmer resistor R_{13} . The amount of the feedback changes as a function of the number of weight resistors R_3 from 330 to 17, thus resulting in a variation of the amplifier input impedance from 0.8 to $15\ \Omega$, i.e., by a factor of almost 20. This leads to a dependence of the summator gain on the number of operating inputs, which is extremely unacceptable, because during spectrometer operation (for example, when performing calibration measurements), PA may be switched off by switching off supply voltages in groups or individually.

To eliminate this dependence, the emitter followers on $Q_{1.1}$ – $Q_{1.19}$ are included in the summator circuit. They isolate the weight resistors incorporated in the feedback from the input circuits. The summator input impedance determined by the R_1 resistance value is 50

Ω .

The potentials at emitters of input followers and at the Q_2 base are almost equal. Therefore, the voltage drop at the weight resistors is small, allowing for their dc coupling. Nevertheless, due to a large number of summed channels, an additional direct current of ~ 0.5 mA appears in the feedback and produces a voltage drop of ~ 3 V across resistor R_{12} and R_{13} . This factor was taken into consideration when calculating the circuit operation for the dc. The trimmer resistor R_5 sets the Q_2 and Q_3 collector currents equal to each other.

The emitter follower Q_4 included in the common NFL creates an additional pole in the frequency response of the amplifier, decreasing its upper boundary frequency and increasing the phase shift at higher frequencies. The frequency response is corrected with a C_4 by proceeding an optimal form of the transient characteristics.

Pulses with an exponential fall time duration of $\sim 80 \mu s$ are formed at the output of the linear summator of the NC channel. These pulses have front duration determined by the features of an event in a counter and range from 1 to $6 \mu s$.

2.3.2 PMT channel

The signals from PMT preamplifiers are joined just as in the NC channel with only one difference. PA are placed immediately on the PMTs HV dividers for minimization of parasitic capacitance in their input circuits and were closed by the light-protecting cover. Therefore, the trimmer resistors which are placed on the PA printed boards inaccessible for operative adjustments, and they are used for preliminary adjustments only. Exact gain equalization of separate PMTs is performed with the help of trimmer weight resistors of linear summator (which is mounted under the top of the light-protecting cover), which axes are available through the top of the cover under slot.

An electric circuit diagram of the fast low-noise linear summator is shown in Figure 4. It was made on the base of well-known scheme of Radeka [2, 3] which was optimized for power voltages ± 12 V. This is inverting amplifier with common parallel voltage NFL. It is built on the base of cascode circuit Q_2 – Q_3 and output stage with bootstrap on Q_4 and Q_5 .

This choice is conditioned by requirements of more high speed of response and linearity of the PMT channel, which provides the future possibility of γ -ray background discrimination in wide dynamic range with using of current pulse waveform from PMT anode.

The first stage of the cascode is performed on bipolar transistor Q_2 which transconductance $S \simeq 100$ mA/V for collector current $I_c = 2.5$ mA (this is optimal mean which is adjusted by trimmer R_5), what exceeds the mean of this parameter for best FETs with factor 5–6. This approach permitted an easy way to compensate the loss of gain at the expense of low power voltages of scheme. The gain of amplifier with open NFL is ~ 12000 . The range of gain adjustment with closed NFL which is controlled by trimmer weight resistors $R_{3.1}$ – $R_{3.3}$ is equal 1–5 in this case. The minimum amount of feedback is > 60 dB. The basic parameters of PMT summator are given in the Table I for the gain equal 3.

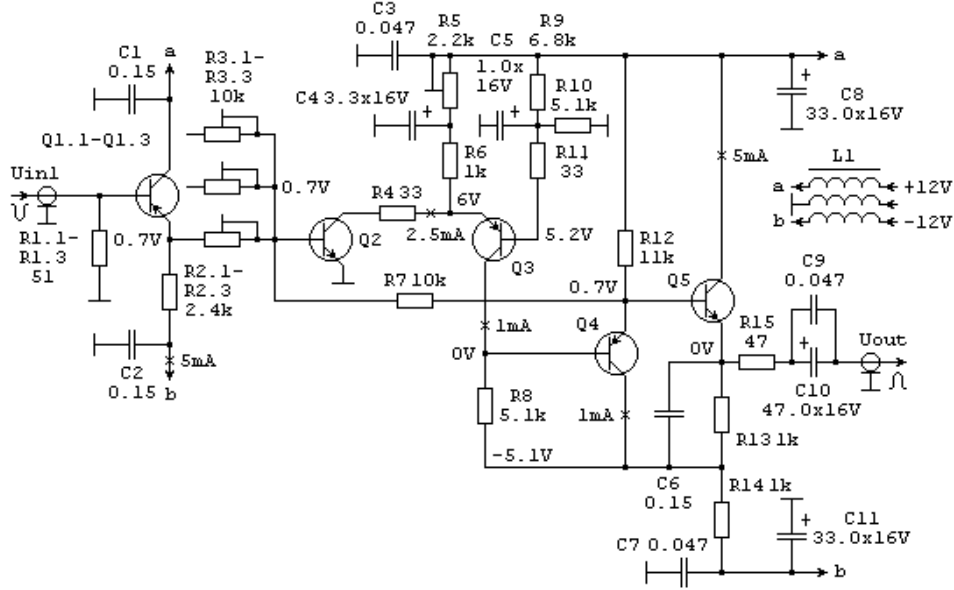


Figure 4: The circuit diagram of a fast low-noise linear summator (PMT)

3 Data acquisition system

3.1 Overview

The third generation of the data acquisition system is described here. The first system was based on slow electronics, a hardware delay line of $80 \mu\text{s}$, and a multichannel analyzer used for data storage and indication. The second acquisition system was previously described in detail [1].

A data acquisition system, whose functional diagram is shown in Figure 5, can be conventionally divided into three parts: the PMT channel, the NC channel and measuring part which includes fast (100 MHz) two-channel PC/AT interfaced digital oscilloscope (DO), and several supplementary units.

Negative signals from the anodes of the three PMTs are entered to the inputs of the preamplifiers. The sufficiently high speed of response and a small input capacitance make it possible to study the feasibility of γ -ray background events discrimination by their waveforms. A continuously adjusted PA gain ensures the operation of all three PMTs from a single high-voltage power supply.

The PMT signals from PA outputs are multiplexed by a fast inverting linear summator and then ramified on two directions. One branch entered directly to the input of the first channel of DO. In the other branch, the PMT signals are entered to the input of combined unit of amplifier and single-channel analyzer (SCA). The positive TTL-specified signal from SCA output triggers the DO through an external trigger input.

In the NC channel, a high voltage of positive polarity from a single source is applied through high-voltage isolating resistors to the anodes of helium counters. The latter generate

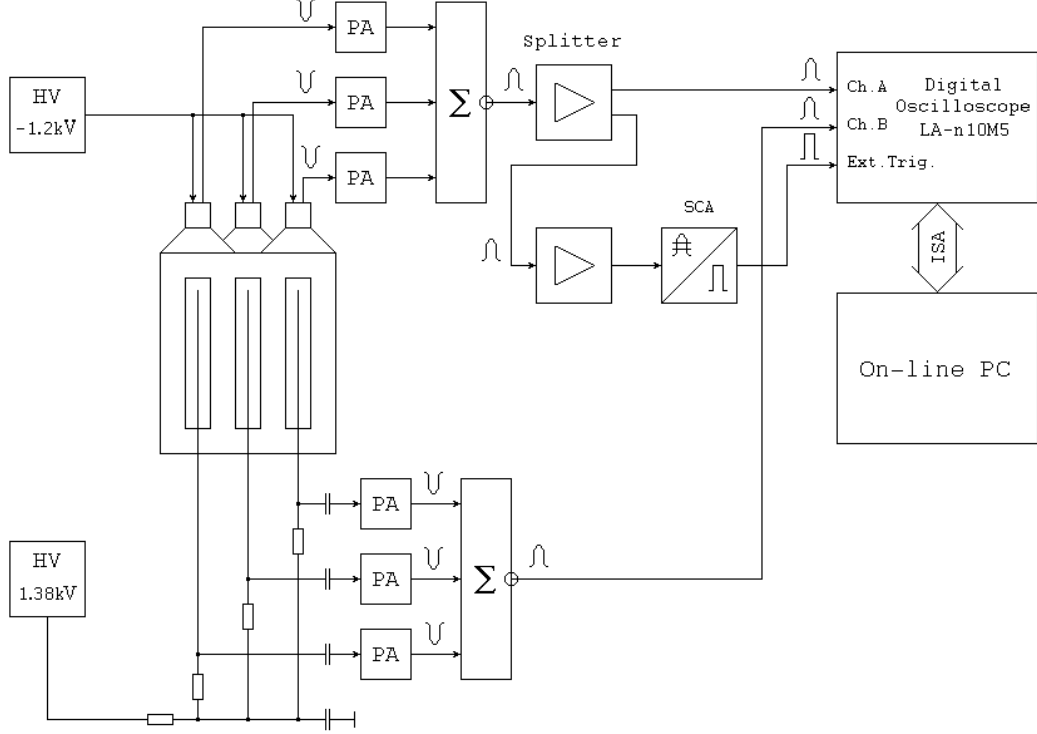


Figure 5: The functional diagram of a data acquisition system

signals of negative polarity, which are fed through high-voltage separating capacitors to the inputs of PAs. The spread of the counters gas amplification factor is cancelled by adjusting the PA gain during calibration. For convenient channel tuning, each of them (similarly to the PMT channel) can be switched off independently by turning off the PA supply voltages.

The signals of neutron counters from the PA outputs are multiplexed in a single channel by using a fast inverting linear summator and subsequently enter directly to the input of the second channel of DO.

The waveform of events in the NC channel is recorded also and ensures the feasibility of discrimination α -particles background by means of mathematical analysis methods.

3.2 Digital Oscilloscope

Two-channel digital oscilloscope model LA-n10M5 (Rudnev-Shil'aev Co., Russia) [4] is used as the base of spectrometer data acquisition system. Its main performance data are listed in the Table 2.

This unit is a 3/2-sized (103×245 mm²) standard printed board placed in an arbitrary ISA-bus slot of the PC/AT-compatible computer.

The start of conversion is produced by one of the input analog signals or an external trigger signal. The synchronization can be performed by edge or level.

An order of internal cyclic RAM operation is following. After the start of conversion command the data from an ADC is continuously written to the selected part of RAM which is called "prehistory". Synchronization pulses are blocked until the volume of prehistory is

Table 2: Main performance data of the digital oscilloscope model LA-n10M5

Number of independent A/D channels	2
Word length (resolution) of A/D conversion	8 bit (256 digitalizing levels)
Sample frequency range *	3.052 kHz – 50 MHz (two-channel mode) –100 MHz _{max} (one-channel mode)
Digitalizing period range *	20 ns (two-channel mode) – 10 ns (one-channel mode) – 0.3277 ms
Volume of internal RAM *	up to 256 kB (up to 128 kB/channel)
Input sensitivity *	$\pm 1V$, $\pm 0.5V$, $\pm 0.2V$ or $\pm 0.1V$
Input impedance	1 M Ω and 15 pF
Signal-to-noise ratio	47 dB
Coefficient of harmonic distortions	–51 dB

* — programmable value

not filled up. After prehistory filling and triggering by the synchronization pulse the part of RAM is written with the deduction of prehistory volume. This part of RAM is called “history”. There is a possibility of switching sample frequency from current value to 50 or 6.25 MHz after finishing prehistory records and arrival of synchronization pulse.

The data from oscilloscope RAM can be transmitted into computer memory in the DMA mode.

The acquisition software is written on C language using Borland C++ compiler. It use all performance of the unit and operates under DOS command prompt mode in MS Windows-95 operation system.

3.3 Operation Algorithm

As was mentioned above, a certain time delay of the signal from NC relative to its PMT signal is a characteristic feature of the detector. Therefore, it is important to select correctly the watching time interval (WTI) for acquisition system. The delay time distribution is of an exponential type $e^{-t/T}$, where t is the delay time and T is the mean lifetime of thermalized neutron in the detector volume. The direct measurement of the delay time distribution of true neutron events was performed [1] with a Pu-Be source. This distribution corresponds to the mean life time value $T \sim 80 \mu s$. The WTI should be selected on the basis of this value. Its particular value depends on background conditions mainly under which measurements of the neutron fluxes are performed.

There are two basic operation modes of the acquisition software: Pulse Acquisition Mode and Spectrum Acquisition Mode.

Pulse Acquisition Mode is usually used for real background measurements. In this mode acquisition is triggered by signal from NC channel. Value of WTI equal $164 \mu s$ is selected what corresponds to 8 kB/channel of the DO RAM for digitizing period equal 20 ns. Therefore, one event is occupied about 16 kB of memory. The prehistory volume is programmed

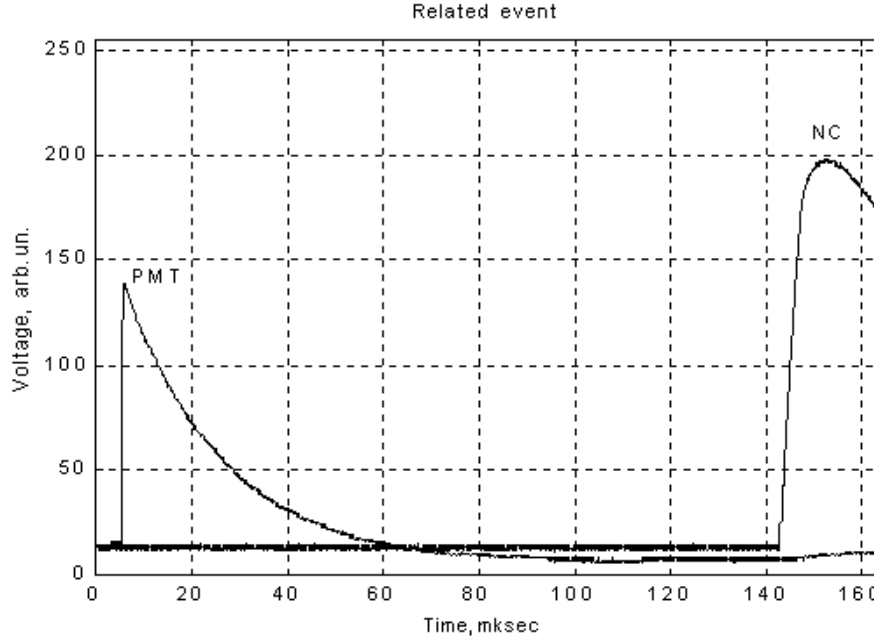


Figure 6: The typical related neutron event

on the value 14/16 parts of WTI, i.e. it is occupied 7 kB of memory or 143 μ s of the time scale. The full waveforms of events in both channels of DO inside WTI are written to the hard disk of computer with using a binary format of data. The maximal counting rate in this case is about 8 events/sec for on-line computer with 133 MHz Pentium-S processor. There is a possibility to decrease the space of memory which occupied by an event at the expense of information about front pulse shape of an event in PMT channel. In this case not all information about an event is written. In the NC channel the frame only with dimensions ± 512 bytes from the prehistory/history boundary, which includes front pulse shape, amplitude and the part of slope of an event is written to the hard disk with the digitizing period equal 20 ns. In the PMT channel each first, eighth, sixteenth etc. digitizing points only inside WTI are written. Therefore, this technique allows one to obtain decreasing factor equal 8. Figure 6 illustrates a typical “picture” of the related neutron event, registered by DO.

Secondly, Spectrum Acquisition Mode, is used for calibration procedures, system operation stability control and background rate monitoring during acquisition. In this mode system is externally triggered by signals from SCA. This performance allows to select the threshold of acquisition more exactly then in case with using of internal triggering. One-channel mode with maximal sample frequency equal 100 MHz and 1 kB of DO RAM, what corresponds to 10 μ s of the time scale, are used. The prehistory volume is programmed on the value 4/16 parts of the time scale. The amplitude and histogram (projection onto amplitude scale) spectra of events are calculated on-line and are written to the hard disk of computer with using an ASCII format of data. The maximal counting rate in this case is about 120 events/s. During background measurements this mode starts automatically on 5 min. after “write-to-disk” command and repeats during this time after each 55 min. of running in the Pulse Acquisition Mode.

Any alteration of DO set-up (contents of INI file), switching between acquisition modes

or start of acquisition with “write-to-disk” command is accompanied by automatic on-line calculation of “base lines” real position. For this purpose DO is switched on short time to automatic mode of horizontal sweep and minimal value of sample frequency.

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